

## Research

# Assessing factors influencing greywater characteristics around the world: a qualitative and quantitative approach with a short-review on greywater treatment technologies

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## Abstract

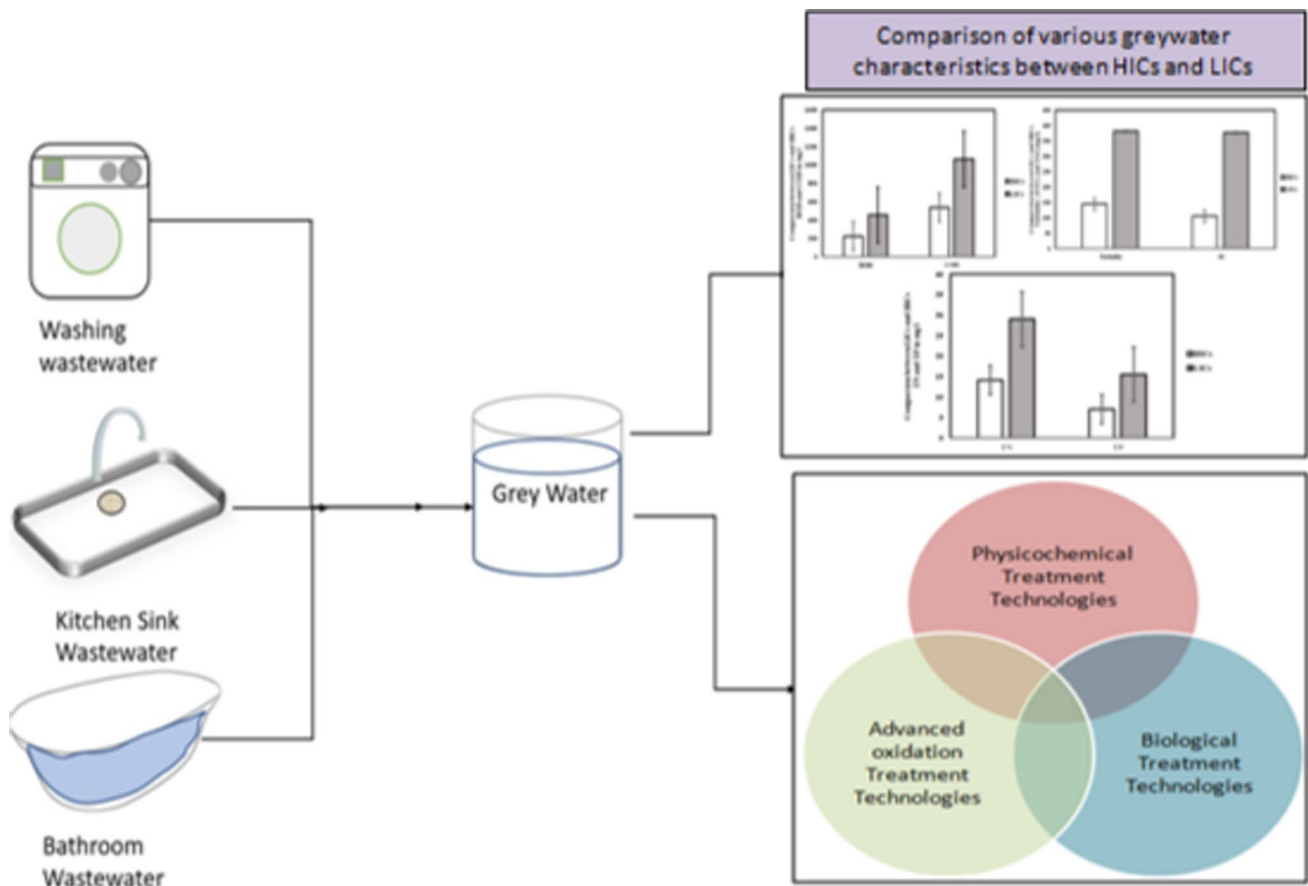
The obsolete efficiencies in conventional centralized wastewater treatment systems call for implementation of source separation and treatment of wastewater. Approximately 60–75% of domestic wastewater is attributed to greywater, which could be reused to combat freshwater crisis. The present study investigates qualitative and quantitative attributes of greywater from different sources in High-Income Countries (HICs) and Low-Income Countries (LICs). The quantity of greywater generation is positively correlated with country's per capita income, but feebly negatively correlated with temperature. Kitchen source is the highest contributor of total suspended solids (134–1300 mg/l), whereas in case of turbidity, laundry is the major contributor (39–444 NTU). Also, kitchen greywater is characterized by comparatively high biochemical oxygen demand (BOD) of 100–1850 mg/l, low pH of 5.6–8, and elevated total nitrogen (TN) of about 1.5–48 mg/l. The high pH (7.3–10) and chemical oxygen demand (COD) levels (58–2497 mg/l) in laundry greywater are due to usage of sodium hydroxide-based soaps, while usage of wash detergents containing phosphates like sodium tripolyphosphate contribute to high total phosphorus (TP) (0.062–57 mg/l). The qualitative characteristics of greywater in HICs are perceived to be superior compared to LICs. Furthermore, the most widely used physicochemical, biological, and advanced oxidation treatment technologies for greywater are outlined briefly. It can be observed that economical treatment systems like phytoremediation or biological technologies combined with sand filtration systems can be implemented to treat greywater with high organic content in LICs, whereas in HICs where greywater is generated in large quantities, electro-coagulation combined with advanced oxidation technologies can be used to treat its higher COD levels.

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## Graphical Abstract



## Highlights

- Assessment of variations in qualitative and quantitative characteristics of greywater from various sources and in HICs and LICs.
- The quantity of greywater generation is positively correlated with the per capita income, but feebly negatively correlated with the temperature aspect of the country.
- Kitchen is the major source of BOD5 and TN, while laundry is the major contributor of COD and TP in the greywater.

**Keywords** Greywater characteristics · High-income countries · Low-income countries · Wastewater · Treatment technologies

## 1 Introduction

Uncontrolled surges in population, urbanization, and industrialization across the globe are elevating the stress on natural resources like water, land, and energy. Water is a vital component, plays a crucial role in many economic pursuits, human well-being, and in the survival of an ecosystem [1]. Water contributes up to 70% of the earth's surface, out of which only 2.5% is available as freshwater, making it a scarce resource. Since 1966, a prodigious decrease of 55% has been observed in the availability of global freshwater [2]. In 2018, more than 2 billion people in the world were prone to high water stress

[3]. In the present scenario of water usage practice, it was estimated to have around one-fourth of the children population of the globe living in water stress-prone areas by 2040 [4]. As per the reports of 'The Coming Global Water Crisis (2012)', the present practice of water usage, a global call for water demand, exceeds the sustainable supply of water resources by 40% in 2030 [5]. On the other hand, conventionally designed centralized treatment plants like sewage treatment plants (STPs) for treating wastewater emerging from domestic and industrial usage of water are running out of capacity. As a result, only 20% of generated wastewater is treated, and the rest 80% is discharged being untreated into surface waters [2, 6]. Studies suggest that the worldwide emissions of CH<sub>4</sub> and N<sub>2</sub>O originating from wastewater treatment plants will surpass 600 million tons and 100 million tons of CO<sub>2</sub> equivalent by 2030, correspondingly [7]. This signifies the pressing need to implement sustainability in these treatment systems. Water as transport media for waste should be reduced or eliminated for sustainable growth. Public health is the major governing factor for the conventional paradigm of centralized operations units. Shortly demographic and economic trends across the globe obsolete the conventional gravity-based sewer system. A need for a paradigm shift is necessary to ensure optimum utilization of resources and for sustainable progress [8]. Separation, treatment, and recycling of the greywater is important to tackle the increasing water demand and overburden on centralized wastewater treatment systems across the globe.

Greywater is defined as the domestic wastewater emerging from households mainly by excluding the toilet wastewater. This greywater accounts for up to 60-75% of the produced domestic wastewater and can be increased to 90% by installing vacuum toilets [9–15]. 10–38% of potable water demand can be decreased by reusing the greywater for toilet flushing [16–18]. Greywater decentralized treatment plants consume 11.8–37.5 % of energy compared to centralized treatment plants serving the same number of inhabitants and proving to be energy efficient [19]. Multiple reasons for greywater reuse in order to alleviate water stress and load on conventional STPs make recycling greywater an emotive and interesting subject.

Untreated greywater poses a high risk to human and plant life. The treatment of greywater mainly depends on characteristics of greywater and the intended end-use of it. While a number of studies have focused on the literature on the treatment options for greywater [20–22], very few reported on the characteristics of greywater. The current study aims to comprehensively examine the distinctive characteristics of greywater generated by assessing its quantitative and qualitative contributions with respect to diverse greywater sources (such as bathroom, laundry, kitchen, and mixed greywater). A comparative analysis is performed to understand the variations in greywater characteristics with the economic levels of the countries. This paper also briefly details the advantages and disadvantages of most commonly adopted physicochemical, biological and advanced oxidation technologies for the treatment of greywater.

## 2 Greywater definition

Conventionally wastewater emerging from the bathroom, laundry, and kitchen sources is coined as greywater. On a different note, domestic wastewater that flows by avoiding the contact of toilet waste is also entitled greywater [12, 23–27]. Additionally, greywater is also termed as graywater, light wastewater, and sullage [28]. Since the kitchen source being the highly polluted source in comparison with other sources of the greywater, several studies elucidated greywater, by excluding the kitchen source [8, 29–33]. Furthermore, greywater is also classified as light polluted greywater (LGW) and high polluted load greywater (HGW) based upon the source of greywater [34]. Wastewater from bathrooms is the prominent source in LGW, and wastewater from the kitchen and laundry is the predominant source in HGW. Due to high volume and low contamination, greywater is relatively easy to treat and reuse compared to wastewater [35].

## 3 Quantity and quality of greywater

The quality and quantity of domestic water supply, the type of water distribution systems, household lifestyle activities, and the origin of greywater are recognized as significant factors influencing the quality and quantity of greywater worldwide [12, 17, 35–38]. In turn, the above factors predominately depend on the region's economy, demography, and climatic conditions. To understand the predilection among economy, demography, and climate conditions on greywater quantity and quality, Pearson correlation is performed among per capita income, average temperatures of the region, and percentage population contribution to the world's total population with the quantity of greywater. Accordingly, countries with a per capita income less than US\$12,535 are classified as low-income countries and, contrary, as high-income countries [39].

For the present study, research articles were obtained through keyword search using the ‘advanced search’ option of the search engine ‘Google Scholar’. To ensure broad coverage of the studies from the database, several keywords have been used for the search and data extraction (‘with at least one of the words’ search option is used for finding articles in the ‘advanced search’), which includes “greywater”, “high income countries”, “low income countries”, “sullage”, “kitchen wastewater”, “bathroom wastewater”, “laundry wastewater”, and “country-wise”. With further sorting, a total of 104 research articles were obtained from the year 2000–2020 in the language of English, related to greywater, in which about 60 HICs and 44 LIC were later observed. These Pearson Correlation (Table.1) elucidates the prolific significance of per capita income in greywater generation. However, the quantity and quality of greywater are inversely related to each other on account of dilution. So, accordingly, in the present study, quantity and quality trends of greywater are mainly focused on the income variation of the country.

The positive correlation between population and quantity of greywater obviously indicates that higher the population greater the quantity of greywater generated. The relation between per capita income and the quantity of greywater generation is positively related whereas the population and temperature with the per capita income are seen to be negatively correlated, which shows that low income countries generally showed higher populations and are generally higher temperature regions (arid regions) and vice versa. Therefore the negative correlation of temperature concerning the quantity of greywater (Table 1), clearly explains arid regions’ low availability of water.

### 3.1 Quantitative characteristics of the greywater

Global production of wastewater is estimated to be about 358–361.4 billion m<sup>3</sup> per year. Geographical region-wise production of wastewater in volumetric terms is estimated as about 74.7 billion m<sup>3</sup> per year in North America, 42.1 billion m<sup>3</sup> per year in Latin America and Caribbean, 38.5 billion m<sup>3</sup> per year in Western Europe, 21.9 billion m<sup>3</sup> per year in Middle East and North Africa, 11 billion m<sup>3</sup> per year in Sub-saharan Africa, 25.6 billion m<sup>3</sup> per year in Southern Asia, 28.2 billion m<sup>3</sup> per year in Eastern Europe and Central Asia, and 117.3 billion m<sup>3</sup> per year in East Asia and Pacific regions [40].

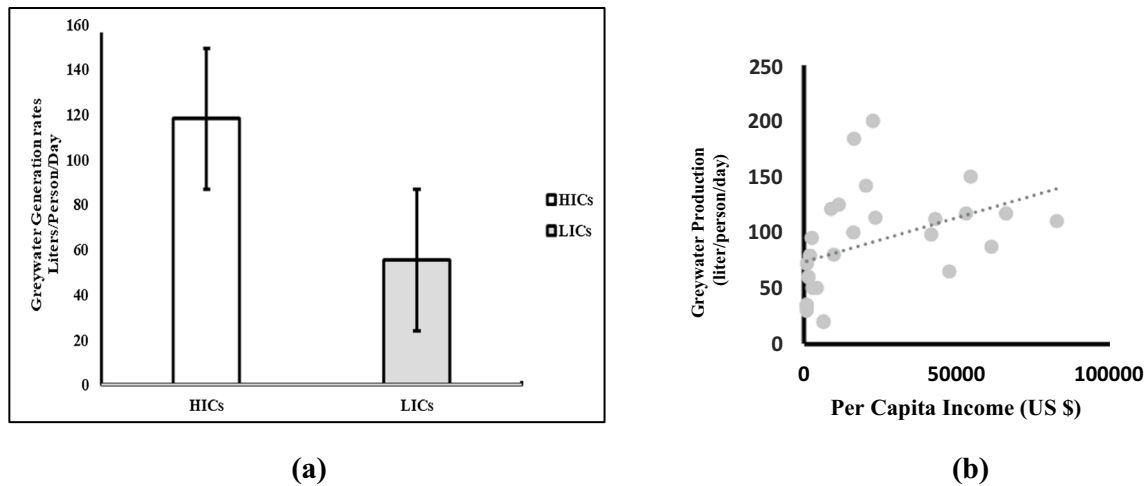
In general, greywater contributes up to 60–75% of total domestic wastewater, and it may even reach 90–100% in households with dry toilets [41–43].

Low-income countries, where the water supply systems are in the rudimentary stage tend to produce a very low quantity of greywater (Fig. 1). Developed countries of Asia, the USA, and Europe tend to produce greywater quantities up to 72–225 lpcd, 200 lpcd, and 35–150 lpcd respectively [28, 44]. By embracing eco-friendly village traditions in multiple regions of Germany, Holland, Sweden, and Norway, Europe has positioned itself as the least prolific generator of greywater when contrasted with Asia and the USA. Low greywater generation rates in South Africa are mainly due to river water usage for personal hygiene and cleansing action [45]. Developing countries noticeably exhibit high percentages of greywater production from total domestic wastewater compared with developed countries (Fig. 2). In countries like South Africa, greywater is about 65–80% of total domestic wastewater elucidates the use of Arabic toilet systems, which might be the probable reason for the high percentage of greywater generation in the middle east countries [46, 47].

In total, bathroom greywater accounts for up to 50–60%, laundry greywater 30–40%, and kitchen greywater 10–30% of total greywater [12, 48–50]. Climatic constraints in the warm climate tend to generate a high percentage of bathroom greywater in comparison with cold climate countries. The percentage contribution of bathroom and laundry greywater is high in the LIC, whereas in case of HIC, the proportion of kitchen greywater is higher. LGW embellishes being the prolific contributor of the greywater with minimal pollutants and maximum quantity compared to HGW.

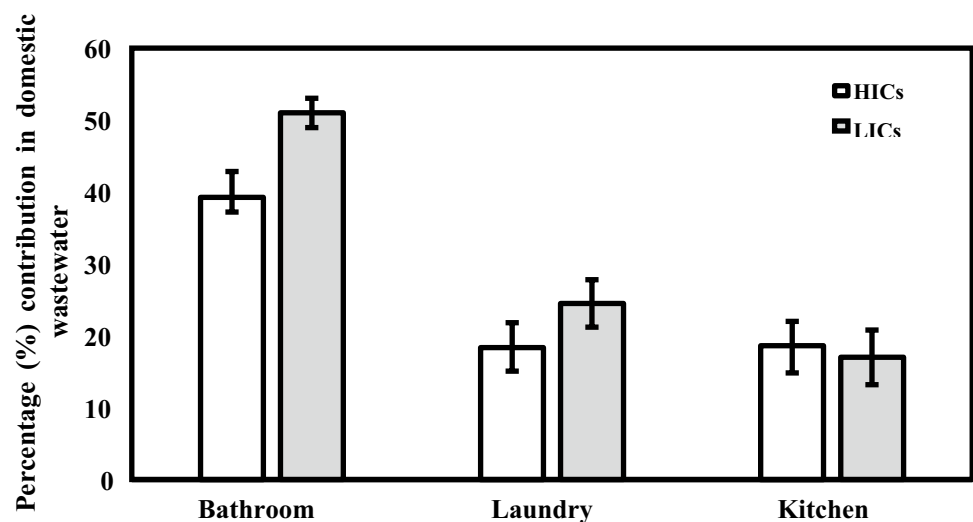
**Table 1** Pearson correlation among the quantity of greywater, population, temperature, and per capita Income

	Quantity of grey-water	Population	Temperature	Per capita income
Quantity of Greywater	1			
Population	0.01	1		
Temperature	– 0.12	– 0.01	1	
Per capita Income	0.40	– 0.20	– 0.67	1



**Fig. 1** Greywater quantity concerning the income levels. **a** Comparison of greywater quantity rates within LICs and HICs. **b** Greywater production with respect to per capita income

**Fig. 2** Contribution of the bathroom, laundry, and kitchen source for the total quantity of greywater generated in LICs and HICs



## 3.2 Qualitative characteristics of greywater

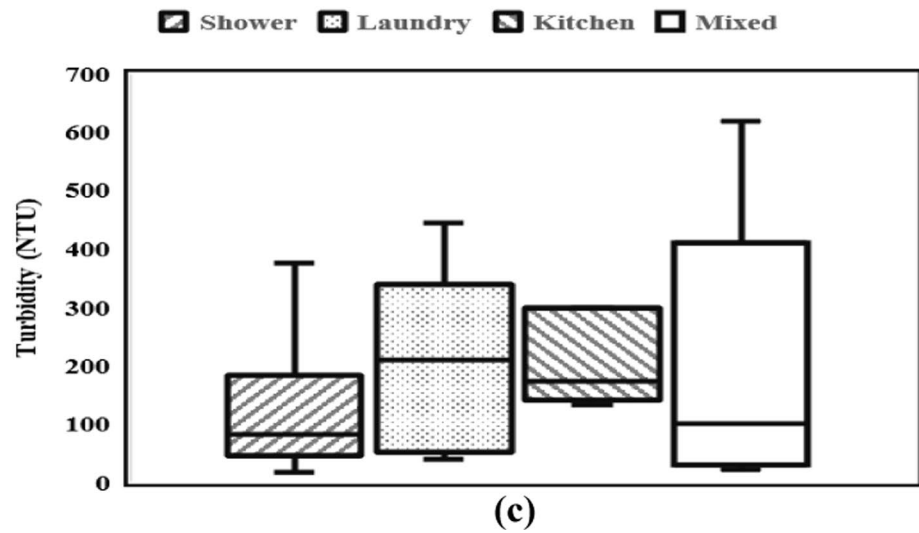
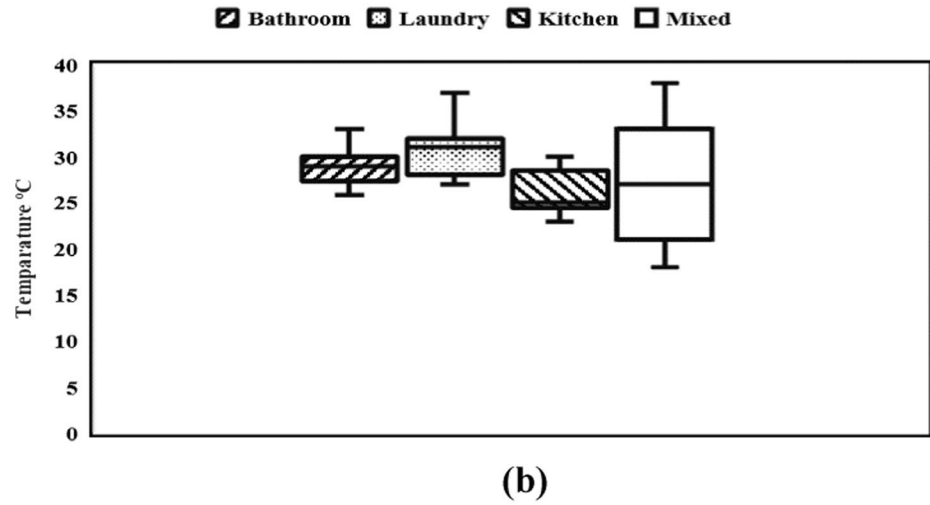
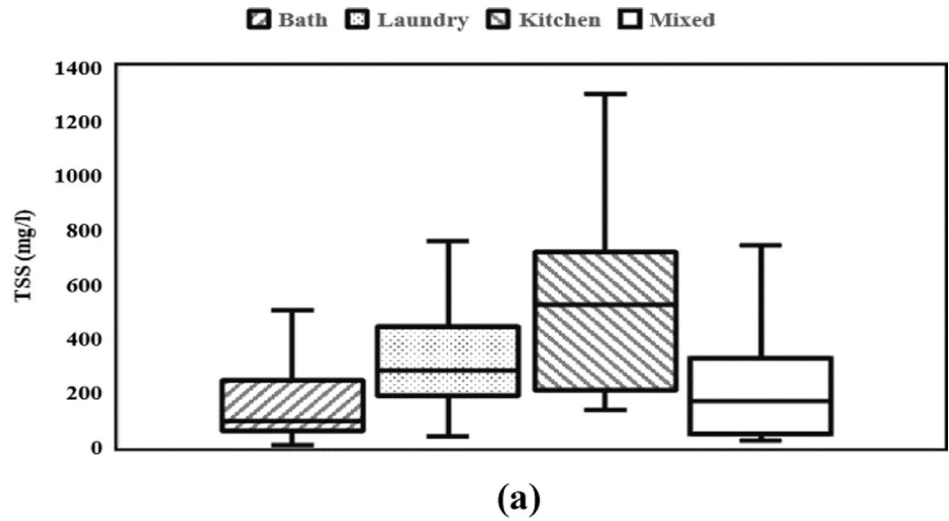
Treatment operation for the greywater predominantly depends upon the qualitative characteristics of the greywater. Recalcitrant trace contents of soaps, detergents, and salts deteriorate the greywater quality. Considerable disparities in greywater quality are evident among different sources of origin. So, the present study examines the physical, chemical, and biological parameters of greywater originating from various sources, taking into account income variations.

### 3.2.1 Physical characteristics of greywater

The present study primarily investigates total suspended solids (TSS), turbidity, and temperature of the greywater. Fig. 3 and Table 2 elucidate the variation in TSS, turbidity, and temperature.

Raw animal fluid and food particles from kitchen wastewater, hair, sand, clay, and non-biodegradable fibers from bathing and laundry wastewater, are the source for solids particles in greywater [51, 52]. Lofty variation in total solids concentration 23–740 mg/l is observed in the mixed greywater and the kitchen source being the highest contributor with an observed variation of (134–1300 mg/l), followed up by laundry source of the greywater (Fig. 3a). On average, suspended solid in greywater makes up to 25–35% of domestic greywater [53].

**Fig. 3** Physical characteristics of greywater from different sources **a** TSS **b** Temperature **c** Turbidity



**Table 2** Physical characteristics of greywater from different sources

	Bathroom	Laundry	Kitchen	Mixed
TSS (mg/l)	7–420	39.5–736	134–1300	23–740
Turbidity (NTU)	17.1–375	39–444	133–298	20–619
Temperature (°C)	25.8–33	27–37	23–30	18–38

High values of turbidity (39–444 NTU) are noticed for greywater emerging from laundry greywater when compared with kitchen and bathroom sources of the greywater (Fig. 3C). In the laundry cycle, the washing cycle produces a marginally high value of turbidity in comparison with the rinse cycle [29]. The Paramount, laundry detergent residues, fabric softeners, and wastage in the laundry and kitchen sources are the reasons for the elevated turbidity levels in the greywater.

The temperature of greywater is noticed to vary from 18 to 38 °C for mixed greywater, 25.8–33 °C for bathroom greywater, 27–37 °C for laundry greywater, and 23–30 °C for kitchen greywater (Fig. 3b and Table 2). The usage of warm water for personal hygiene elevates the temperature of mixed greywater resulting in high microbial activities and stimulating incrustation on walls or pipes [54]. Compared with domestic wastewater, the high temperature of greywater assists in both aerobic and anaerobic degradation of organic matter. Since the optimum temperature for aerobic and anaerobic degradation varies in the range of 15–50 °C and 25–35 °C [55].

### 3.2.2 Chemical characteristics of greywater

The principal parameters of chemical characteristics, biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and pH are envisaged in the present study. Table 3 and Fig. 4 describe the variation of chemical characteristics for the selected parameters.

Alkalinity and pH of the domestic water supply primarily influence the pH of greywater [17]. Greywater from the laundry source is the main reason for the high pH values of 7.3–10. Usage of sodium hydroxide-based soaps in laundry greywater results in elevated pH levels. The presence of polyunsaturated fatty acids, monounsaturated fatty acids, and saturated fatty acids in cooking oils is the foremost cause for the slightly acidic pH (5.5–8) of the kitchen source (Table 3, Fig. 4).

Detergents are the main source of the hoisted level of COD in greywater. Mixed greywater is reported to vary between 25 and 2278 mg/l of COD and 14–840 mg/l of BOD<sub>5</sub>. Extravagant use of detergents for laundry purposes makes the greywater originating from the laundry have high COD levels with a concentration range of 58–2497 mg/L. Washing of vegetables, meat, etc., makes kitchen greywater have high BOD<sub>5</sub> values with a concentration range of 100–1850 mg/l. In comparison, domestic wastewater from households is intimated to have 210–740 mg/l and 150–530 mg/l of COD and BOD<sub>5</sub>, respectively [56]. Due to less suspended solids concentration when compared with domestic wastewater, greywater poses most of COD and BOD<sub>5</sub> in the soluble form [28].

Proteins in the meat, food, and ammonia-containing cleansing products are the prolific contributors of nitrogen in greywater. Urine is the primary source of nitrogen compounds in domestic household wastewater, where the urine in greywater making it contaminated with a total nitrogen concentration of 1.7–36 mg/l in mixed greywater, with kitchen wastewater being the main source of total nitrogen concentration (1.5–48 mg/l) in comparison with laundry (0.9–40.3 mg/l) and bathroom (0.5–29 mg/l) sources.

The usage of washing detergents containing sodium tripolyphosphate for cleaning utensils and washing clothes are the major contributors to total phosphorus, mainly in areas that have not banned phosphorus in detergents [57]. On account of excessive usage of detergents in the laundry, laundry greywater exhibits high level of phosphorus

**Table 3** Chemical characteristics of greywater from different sources

Parameters	Bathroom	Laundry	Kitchen	Mixed
pH	5–8.3	7.3–10	5.58–8	6–8.3
BOD <sub>5</sub> (mg/l)	18–248	38–743	100–1850	14–840
COD (mg/l)	77–600	58–2497	26–2471	25–2278
TN (mg/l)	0.5–29	0.9–40.3	1.5–48	1.7–36
TP (mg/l)	0.04–1.3	0.062–57	1.4–25	0.11–22



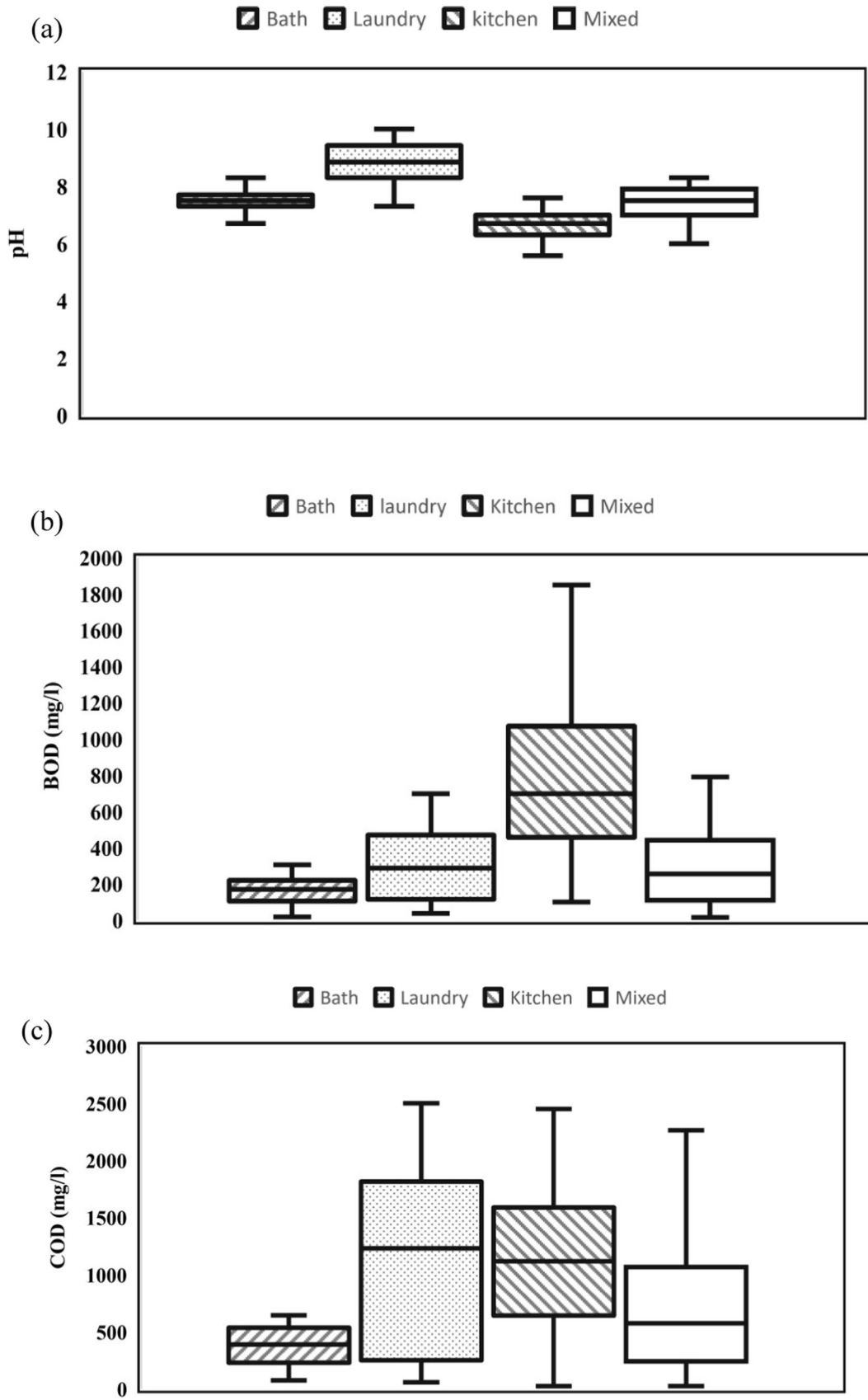


Fig. 4 Chemical characteristics of greywater from different sources. a pH b BOD c COD d TN e TP



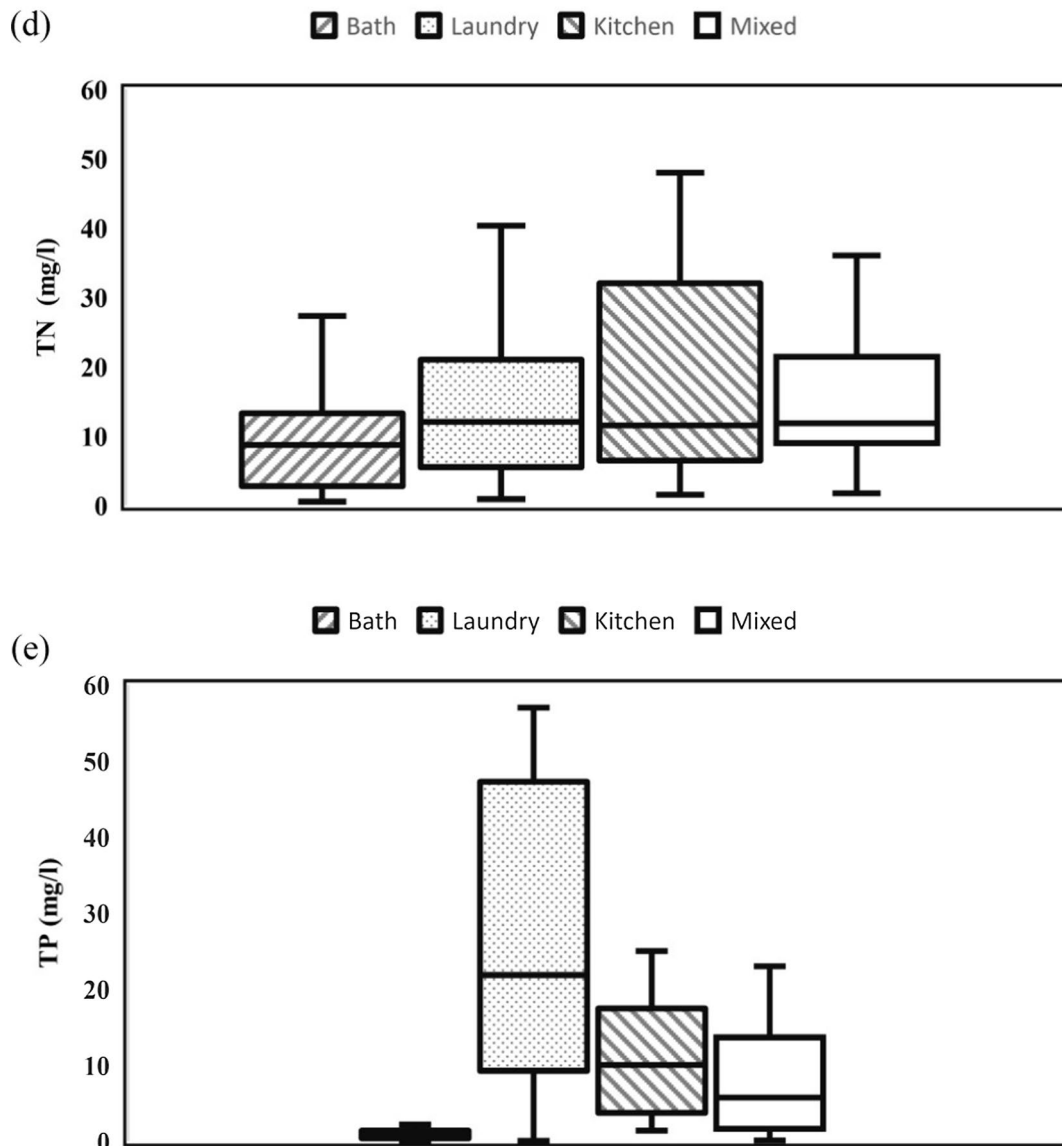


Fig. 4 (continued)

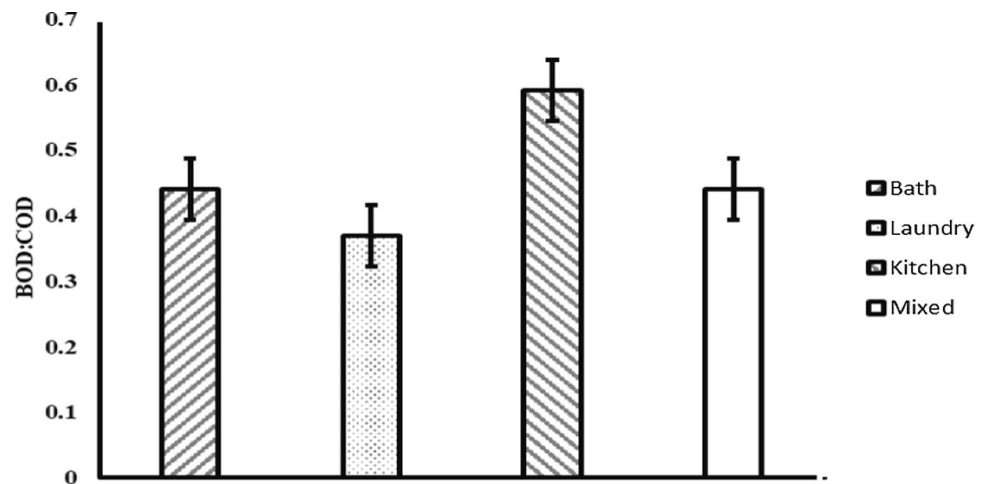
(0.062–57 mg/l) on comparison with bathroom greywater (0.04–1.3 mg/l), kitchen greywater (1.4–25 mg/l) and mixed greywater (0.11–22 mg/l). On average, greywater contributes up to 45–50% of total phosphorus, 35–45% of organic load, and 1–2% of total nitrogen in domestic household wastewater.

The high value of COD from laundry greywater, 2497 mg/L reported in the study of Uganda slumps [49]. This is mainly due to low usage of water in LICs.

### 3.2.3 Biodegradability of greywater

The biodegradability of the greywater is explained in Fig. 5 by accounting BOD: COD ratio. The averaged BOD: COD of kitchen greywater and mixed greywater are 0.59 and 0.44, respectively, and were in accordance with the optimum values suggested by Alisawi, H. A. O. (2020), indicating good degradability of organic matter [58]. On the other hand, a few values of BOD: COD ratio of laundry and bathroom greywater were noticed as outliers from the optimum BOD: COD ratio suggested by Metcalf, Eddy, and Tchobanoglous [59]. Knerr et al. [60] observed a balanced BOD: COD for mixed greywater

**Fig. 5** BOD:COD ratio of greywater from the bathroom, laundry, kitchen, and mixed greywater sources



as suggested by Metcalf, Eddy, and Tchobanoglous [59, 60]. Low levels of BOD: COD ratio in the study of Jefferson et al. [61] are mainly due to the exclusion of kitchen greywater [61].

### 3.2.4 Biological characteristics of the greywater

Bodily contact with the greywater is the main source of the intrusion of helminths, protozoa, and bacteria. *Pseudomonas*, *Giardia*, *Legionella*, *Cryptosporidium*, and *Staphylococcus aureus* are usually noticed in the greywater [62–68]. Total Coliform (TC), faecal Coliform (FC), and E-coli are conventionally considered as microbial indicators. Averaged variations among TC, FC, and E-coli are envisaged from different sources Table 4. Washing hands after toilet use, raw meat, uncooked food, and washing of baby diapers are the anticipated reasons for microorganism contamination. Age distribution predominantly affects the concentration of fecal coliforms [17]. The presence of infants elevates the fecal coliform concentration in the greywater. Moreover, the presence of organic matter accelerates the metabolism of indicator organisms [69]. Washing of nappies may be the probable reason for the elevated levels of FC (Table 4) from the bathroom source and laundry source. Storage and transport of greywater results in elevated levels of microorganisms in mixed greywater [23].

## 4 Additional parameters

### 4.1 Organic micro-pollutants in the greywater

The presence of synthetic chemicals, pharmaceuticals, and xenobiotic organic chemicals (XOCs), which are also called emerging contaminants, whose presence in greywater is increasing in the current times, also tends to increase the COD levels of greywater [35]. Synthetic organic compounds, or XOCs, are found in medications and common household chemicals like softeners, builders, surfactants, bleaches, and cosmetics. Various personal care and domestic products contain surfactants. Because of their great solubility, most of these surfactants enter the wastewater stream without going through any metabolic modifications. Due to this phenomenon, these released substances cause several negative impacts over an extended period of time in the environment [70]. A total of 4.5 million metric tonnes of anionic surfactants, 1.7 million metric tonnes of non-ionics, and 0.5 million tonnes of cationic surfactants were produced worldwide in 2003 [71]. In the Netherlands, based on average typical composition of personal care and household products, anionic surfactants, such as linear alkyl sulfonates (LAS), were present in greywater in the range of  $41 \pm 12$  mg/l, non-ionic surfactants were present at concentrations of  $11.3 \pm 3.9$  mg/l and cationics at  $1.7 \pm 0.8$  mg/l [72]. Greywater frequently contains comparatively large amounts of

**Table 4** Microbial characteristics of greywater from different sources

	Bath	Laundry	Kitchen	Mixed
TC	1.70E+06	2.10E+06	1.00E+07	2.67E+07
FC	3.77E+04	1.05E+05	1.60E+05	1.23E+05
E-coli	3.28E+05	1.85E+06	3.51E+05	1.33E+06

surfactants [73]. Trimethylamine (TMA), a cationic surfactant (~7.84%), propylene glycol (PG), a non-ionic surfactant (~5%), and sodium dodecyl sulfate (SDS), an anionic surfactant (~29.22%), make up the greatest percent of ingredients in the majority of detergents [70]. XOCs are usually resistant to conventional treatment processes and accumulate in the human, plant, and animal bodies by posing a risk to the environment [74]. Eriksson et al. [17], identified 900 potential XOCs by analyzing the various household chemicals [17]. Antibiotics' presence in the greywater results in the development of strains of antibiotics-resistant bacteria [75]. Palmquist and Hanaeus [76], Revitt et al. [77] identified the presence of toxic substances like phthalates, polycyclic aromatic hydrocarbons, triclosan, monocyclic aromatic compounds, brominated flame retardants, 4- nitrophenol, and benzene in the greywater [76, 77]. In personal care products like hand soap, shower, and bathing products, parabens are frequently used as preservatives in concentrations as high as 0.8%. They are more likely to be found in hand basins and shower greywater than in laundry and kitchen greywater [78]. Shaik et al. [79] observed a high concentration of methylene blue active substances (MBAs) in the range of 2.6–55 mg/l and 7–39 mg/l for kitchen and laundry sources, respectively, and even observed a high concentration of LAS in the range of 7–87 mg/l and 8.8–118.3 mg/l for kitchen and laundry source respectively [79]. Several studies documented the decomposition of SDS in bio-filtration [80], in anaerobic circumstances [81], and aerobic environments [82]. Additionally, studies have documented SDS adsorption onto soil [83]. Soil biodegradation was used for eliminating PG [84]. Research revealed that TMA can be eliminated via obligatory microbial decomposition [85], bio-filtration [86], and adsorption onto wood ash and activated carbon [85–87].

## 4.2 Metals in the greywater

The high sodium content of the greywater may be due to its use as the counter cation for various anionic surfactants in powdered detergents [88]. Elevated sodium levels are noticed in laundry greywater with a concentration range of 50–302.1 mg/l due to excessive usage of chemical detergents [10]. Among all the ions present in the greywater, Sodium and Boron are considered to be deteriorating ions to the plant life. Elevated sodium levels can alter the electrical conductivity and structure of the soils [89]. Boron from the usage of cleansing chemicals of the households alter the metabolism of carbohydrates and nucleic acid synthesis, eventually leading to plant death [10]. In greywater, heavy metals are also frequently detected. The two heavy metals that are typically found in large amounts are zinc and copper. In studies conducted by Noutsopoulos et al. [90], Zn (0.2–6.3 mg/l) and Cu (1–10 mg/l) were found in bathroom greywater. Usage of acidic natural chloride tablets for disinfection leads to the leaching of Zn and Cu from the pipe walls, resulting in elevated levels of Zn and Cu [90]. There are reports of high Pb concentrations in certain greywater sources. The elimination of outdated lead-based wall paint, which may have left particles in clothing that were later washed in the laundry, and the coatings on lead pipes in the water distribution system are likely sources of lead [91]. A pilot greywater treatment and reuse system (for flushing toilets) at a campsite in Denmark, which included a settling tank, buffer tank, biological sand filter, and disinfection unit, is observed to have removed Pb of about 44% and Cd of about 96% from the aqueous phase [92].

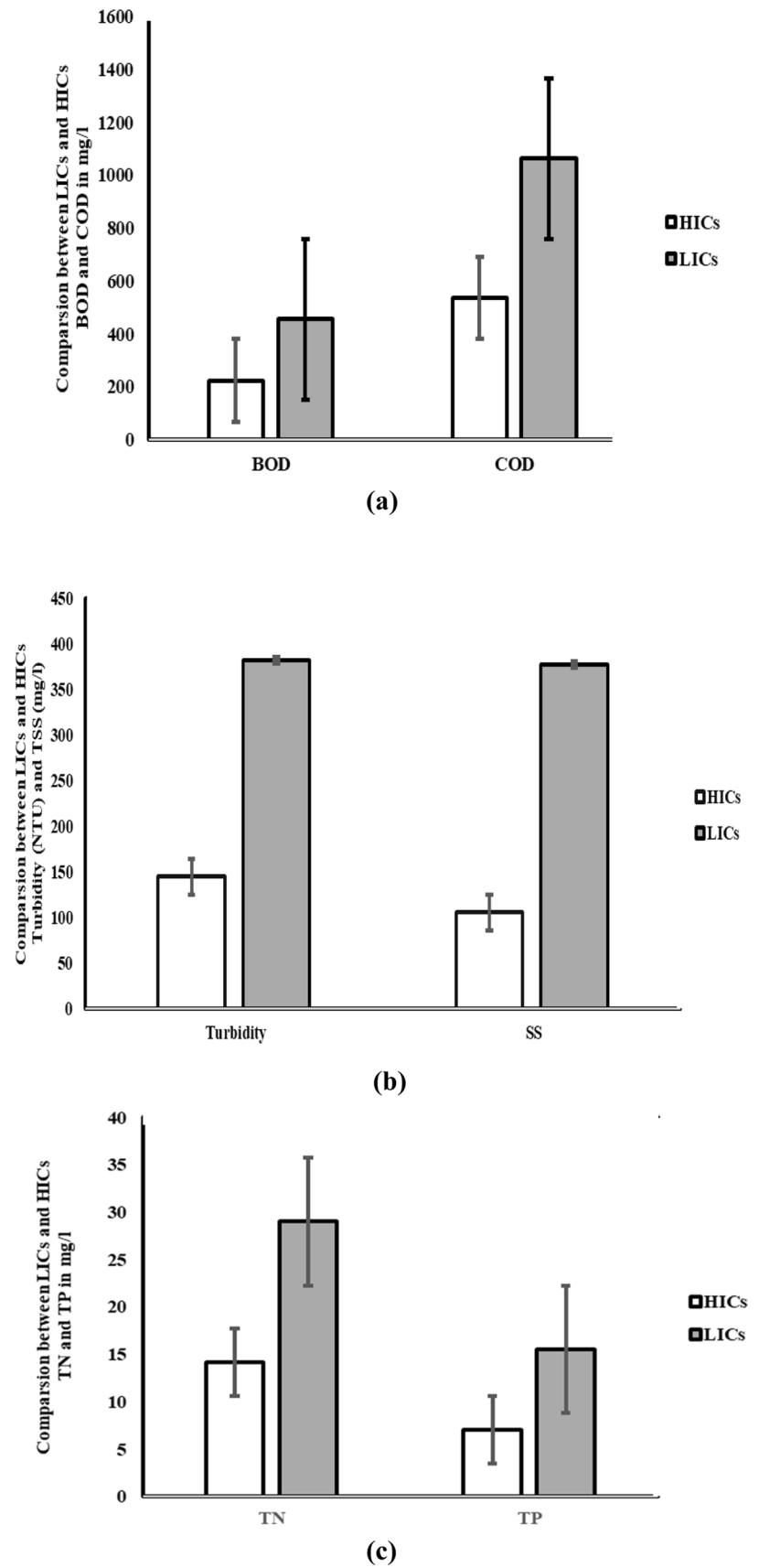
## 4.3 Color and odor of the greywater

The excess presence of humic substances, metals, and other coloring agents in the greywater may permanently change the greywater color [93]. Emerson et al. [94] elucidated the characteristic of changing color into cloudy and grey, even for a short storage time made the greywater entitled 'greywater' [94]. Having said, no constraints are caused owing to color in greywater, but it is always an aesthetic challenge leading to misleading consumer presumptions. The odor of greywater predominantly depends on the lifestyle of the menage. Long-term storage of all kinds of wastewater results in the depletion of oxygen content in the water and enhances anaerobic conditions leading to a peculiar odor. However, the rate of anaerobic degradation in greywater is comparatively slower than in domestic wastewater [95–97].

## 5 Greywater qualitative characteristics in HICs and LICs

After analyzing the various HICs and LICs, mainly for TSS, turbidity, BOD, COD, TN, and TP, greywater emerging from LICs poses derogative greywater quality compared with the HICs. Adequate water supply and enhancement in the technology, in HICs, tend to dilute the greywater, which results in low concentration of BOD and COD, averaged in the range of 223.4 mg/l and 534.78 mg/l for HICs respectively, and on comparison, high concentration of BOD and COD averaged in the range of 455.17 mg/l and 1062.7 mg/l respectively were observed in LICs (Fig. 6a). Usage of alternative sources like open wells in LICs, owing to water scarcity results in high averaged values of turbidity (381.65 NTU) and TSS (376.78 mg/l) in comparison with

**Fig. 6** Comparison between HICs and LICs with averaged values **a** BOD and COD **b** Turbidity and TSS **c** TN and TP



HICs turbidity (144.58 NTU) and TSS (105.5 mg/l) (Fig. 6b). Avoiding the phosphorus content detergents in HICs results in the low average concentration ranges of TP 7.04 mg/l when compared with LICs 15.05 mg/l (Fig. 6c).

## 6 Greywater treatment technologies

This section mainly discusses various types of greywater treatment technologies that have been in practice as of date. The scale of the treatment unit, greywater characteristics, and intended removal efficiency are prolific factors for selecting appropriate treatment technology. Greywater treatment technologies are classified as physicochemical, advanced oxidation, and biological, categorized on the treatment mechanism.

### 6.1 Physicochemical treatment technologies

The sand filters integrated with disinfection units are the most widely adopted physicochemical treatment options in greywater treatment technologies [98]. Sand filters effectively remove the turbidity, TSS, and TDS in the greywater. In the studies conducted by Friedler and Alfiya [99] and Samayamanthula et al. [100] more than 75% removal of turbidity, TSS and TDS was observed [99, 100]. This is mainly due to the hydrophobic nature of sand that strongly attracts TSS. Also, finer particles of sand attract negatively charged colloidal particles through ion exchange and adsorption mechanisms [98]. The formation of a *schmutzdecke* layer in sand filters is one of the significant reasons for removing organic matter. Still, its formation is limited to the sand filters' top surface, resulting in inadequate organic matter reduction in sand filtration treatment units [101]. The efficacy of sand filters can be improved by adopting pre-treatment technologies like coagulation and sedimentation [102]. To overcome the shortcomings of the conventional sand filtration system, Spychała and Nguyen [103] carried out filtration with a geotextile filter with an average pore size of 0.14 mm. In the study, about 68%, 65% and 78% removal of BOD<sub>5</sub>, COD, and TSS respectively was observed. Particle agglomeration and deposition are the significant reasons for removing organic matter and TSS in geotextile filters [103]. In the study of Ramon et al. (2004), ultra-filtration (UF) and nanofiltration (NF) are employed to treat the greywater without any prior treatment [104]. Effluent from UF showed about 45–75% removal of COD and more than 90% turbidity removal with minimal removal of BOD<sub>5</sub>. In the same study, NF demonstrated more than 90% organic matter removal [104]. However, dissolved nitrogen and phosphorous forms can easily pass through UF pores and microfiltration [83]. There is very minimal removal of nutrients like nitrogen and phosphorus in all the filtration systems. Adding coagulants like ferric chloride (FeCl<sub>3</sub>) and calcium hydroxide (CaOH<sub>2</sub>) to greywater showed an excellent removal of COD and BOD<sub>5</sub> and a considerable change in the pH value of greywater during the coagulation mainly due to the reaction between coagulants and nitrates in greywater [105]. Table 5 elucidates various physicochemical treatment technologies for treating greywater.

### 6.2 Advanced oxidation treatment technologies

The potent oxidation radicals like hydroxyl (OH•), superoxide (O<sup>2-</sup>), etc., are generated during the advanced oxidation process (AOPs) [108]. These radicals are non-selective and highly reactive in nature and can degrade any toxic organic compounds like pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), etc., in the greywater.

The photochemical AOPs are most widely operated under the wavelength range of ultraviolet to the visible range of the electromagnetic spectrum. During photochemical AOP, OH• radicals are produced by ionization and excitation of electrons when organic matter in wastewater gets exposed to radiation of energy varying from visible light to ultraviolet light. Chemical AOPs uses chemicals like peroxide (H<sub>2</sub>O<sub>2</sub>), ozone (O<sub>3</sub>), etc., to produce OH• radicals to degrade contaminants in the greywater [98]. Nevertheless, photochemical and chemical AOPs are investigated to have limited removal efficiency in degrading complex organic compounds. This is mainly due to insufficient production of oxidative radicals [109, 110]. Thus, it can be concluded that these technologies are often combined to treat toxic compounds in greywater, i.e., UV/H<sub>2</sub>O<sub>2</sub> or UV/ozone [109]. Rana et al. [111], reported the treatment of the greywater with UV activated peroxide-based AOP and showed an increase in the biodegradability index of greywater by 67%, further supporting smooth removal of contaminants through biological remediation [111]. The ozone assisted through an electrocoagulation study conducted by Barzegar et al. [112] showed a reasonable reduction of TOC and COD by 50% and 65%, respectively [112]. However, the AOPs have a minimal removal of suspended particles, and the presence of suspended matter will inhibit

**Table 5** Physicochemical treatment technologies

Source	Operation	Target parameters	Efficiency/comments	Reference
Semi- synthetic greywater water	Filtration through the non-woven textile filter	TSS, COD, and BOD <sub>5</sub>	The average removal efficiency of treated greywater for BOD <sub>5</sub> and COD is 67.2% and 71.6%. For TSS comparatively high removal of 77.6% is noticed	[103]
Office building of Civil and Environmental Engineering in the Technion, Israel	1. Standalone filtration 2. Combined coagulation, sedimentation and filtration	TSS, Turbidity, COD, and BOD <sub>5</sub>	Standalone filtration was able to remove only 5% of BOD <sub>5</sub> , 70% of TSS, 50% of turbidity. Combined system was able to remove about 57% of BOD <sub>5</sub> , 65% of COD, 92% of turbidity and 94% of TSS	[99]
Synthetic greywater	Nano filtration (NF)	COD, surfactants	NF was able to remove above 95% of both COD and surfactants	[106]
Residential areas of Athens, Greece	Sedimentation, coagulation/ flocculation and Fenton's reaction	TSS, COD, BOD, and oil & grease	The removal rates of TSS, COD, BOD and oil & grease enhanced to 94.9, 91.8, 94.2 and 97.2%, successively	[90]
Synthetic greywater water (Bath and Laundry)	Activated charcoal filters (grain size distribution 0.8–6.3 mm)	BOD <sub>5</sub> and EC	EC was decreased by 7.14% and 98% of BOD <sub>5</sub> removal was observed	[12]
Synthetic greywater water: (Kitchen)	Filtration tank with multiple layers: Coconut shell cover (20 cm) + Coarse Sawdust (15 cm) + Charcoal (20 cm) + bricks (10 cm) + Sand (15 cm) HRT = 24 h	TSS, TDS, Oil-grease, COD, NH <sub>4</sub> <sup>+</sup> N, NO <sub>3</sub> <sup>-</sup> N, PO <sub>4</sub> <sup>3-</sup> P	The filtration system achieved removal rates of 82.61% TSS, 69.98% TDS, 96.97% Oil-grease removal, 82.26% COD, 73.42% NH <sub>4</sub> <sup>+</sup> N, 68.66% NO <sub>3</sub> <sup>-</sup> N, 100% PO <sub>4</sub> <sup>3-</sup> P	[107]

the performance of light penetration, thereby hindering the production of free radicals [113]. A very nominal removal of TSS and TDS is observed in Bhatta et al. [114] under ozone activation through UV [114]. Hence, pre-treatment options for TSS removal should be preferred before AOPs for better removal of contaminants in greywater. In the study conducted by Asaithambi et al. [115], the combination of UV/ H<sub>2</sub>O<sub>2</sub>/ozone showed a better result than UV, O<sub>3</sub> or UV/O<sub>3</sub> for treating greywater [115]. This study showed about 100 % removal of color and COD in 4 hours of treatment time and consumed only 0.01 kWh/m<sup>3</sup> for COD and color removal. However, the AOPs have their shortcomings in removing nutrients like nitrogen and phosphorus. The studies conducted by Bhatta et al. [114] and Hadiyanto et al. [116] showed that there is no reduction in nitrogen and phosphorus [114, 116]. Hence it is evident that stand-alone AOPs cannot remove all the pollution of the greywater. So, they should be integrated with other treatment technologies. Table 6 elucidates various AOPs technologies in treating greywater.

### 6.3 Biological treatment technologies

Oxygen is a significant parameter in the biological degradation of contaminants in greywater. To enhance the bacteria growth in the aerobic biological process, oxygen is disparaged through the aeration process [121]. The viscosity of the solution, the concentration of gas, and the particle size usually control the diffusion of oxygen through aeration [122]. The sequential batch reactor is one of the most widely opted biological treatment technologies and removes COD by 90% in greywater [123–125]. The high removal in the above studies is mainly due to a comparatively high percentage of colloidal COD in greywater that can be conveniently removed by aerobic process [125]. The rotating biological contactor is another aerobic process used frequently in treating the greywater and has demonstrated a good removal of TSS and BOD<sub>5</sub> by 95% and 93%, respectively, as reported by Abdel-Kader (2013) [126].

Nevertheless, these aeration technologies have a significant shortcoming of space requirements, so they fall short in their application to small pilot-scale treatment units. Membrane bioreactor (MBR) is one of the best suitable treatment options for common space or small-scale aerobic greywater treatment technologies. Smith and Bani-Melhem [127] reported that the greywater treatment using MBR demonstrated about 90% removal of TSS and 80% removal of BOD<sub>5</sub> at constant transmembrane pressure, when operated for 50 days [127]. The nutrient removal from greywater with biological processes is better than physicochemical and advanced oxidation processes. In the studies conducted by Lamine et al. [123], about 91% of ammonical nitrogen and 50% nitrite was removed from greywater for an operation period of 2.5 days in the aerobic treatment process while phosphate was also reduced by 66% [123]. Nevertheless, no denitrification happens in the aerobic zone, limiting the complete removal of nutrients in the greywater. The phycoremediation process can be a better replacement for aeration enhanced systems for the removal of nutrients. During the growth of microalgae, it accumulates both nitrogen and phosphorus and releases oxygen into the atmosphere. A study in Ethiopia observed the best performing greywater treatment system with the high pollutant removal efficiencies of turbidity (97.2%), TSS (99.2%), BOD<sub>5</sub>(94%), COD (91.6%), chlorides (61%), TN (68.24), TP (71.6%), and FC (90%) using a combined treatment system of biofiltration and horizontal subsurface flow constructed wetland. The study concludes that this system can be a technology of choice in low-income countries, particularly those with tropical climates [128]. Table 7 lists various biological treatment processes that have been employed for the treatment of greywater.

## 7 Conclusion

Income levels of countries are found to be the prolific reason for variation in greywater quality and quantity across the globe. A high quantity of greywater is generated from HICs mainly due to the existence of proper water supply and the implementation of advanced technologies in water. Therefore, it was observed in this study that the quantity of greywater generation is positively correlated with the per capita income but also feebly correlated negatively with the temperature aspect of the country. Even though the percentage of greywater generated from domestic wastewater is high, overall greywater generation is minimal for LICs due to inadequate water supply and climatic constraints like being arid regions. As a whole, a minimum level of greywater quantity is emerging from the kitchen, but excluding kitchen sources from greywater, makes it deficient in nutrients and organic matter, resulting in low biodegradability. Low physical and chemical contamination values are observed in bathroom greywater compared to other greywater sources. The high concentration of TSS, BOD, BOD: COD, and TN, along with low pH values, are observed from the greywater of kitchen source due to the presence of waste food particles, usage of oils, and soaps for washing utensils. The high concentration of turbidity, temperature, COD, and TP, along with high pH values, are observed from laundry sources mainly due



**Table 6** Advanced oxidation treatment technologies

Source	Operation	Target parameters	Efficiency/comments	Reference
Washing machine	Cold plasma Ozonator	COD, Methyl orange and surfactants	About 68.7% of COD, 66.4% anionic surfactants and 91.9% of methyl orange is removed during treatment	[117]
Student dormitory, JahanAra dormitory, Iran	Electrocoagulation with ozone	E-Coli, COD, TOC, Total coliform (TC)	86% of E-coli, 85% of COD, 70% of TOC, and about 2.9 logs of TC were removed during 60 min of electrolysis time	[112]
Shower, laundry and teeth brushing	Electrocoagulation with ozone activated through UV light $H_2O_2$ activated through UV-C light	COD, BOD <sub>5</sub> ; COD	The results showed about 96% of E-coli, 87% of TOC, 95% of COD, and about 4 logs of TC removal The treatment was able to remove about 87% of COD and BOD <sub>5</sub> ; COD ratio was increased from 0.22 to 0.41 after the treatment	[118]
Greywater from a representative middle-income group household, India	Electrocoagulation with Al electrode	COD, turbidity, pathogens	70% of the total COD, 85% of turbidity and more than 99.9% pathogens could be removed with an energy consumption of 0.3 kW h/m <sup>3</sup> of greywater	[119]
Laundry water from student management laundry, Malaysia	Photocatalytic fuel cell employing ZnO/Zn photoanode and CuO/Cu photocathode	COD, Turbidity, BOD <sub>5</sub> , NH <sub>4</sub> <sup>+</sup> N	55% COD, 88% turbidity, 55% BOD <sub>5</sub> , and 75% NH <sub>4</sub> <sup>+</sup> N removal efficiencies were observed	[120]
Synthetic greywater (shower)	Hybrid granular active carbon with electro-chemical system (boron-doped diamond)	COD, TOC	The system achieved removal efficiencies of 68% of COD and 70% of TOC removal	[63]

**Table 7** Biological treatment technologies

Source	Operation	Target parameters	Efficiency/comments	Reference
Households in Johor Malaysia	Botryococcus algae species	COD, BOD <sub>5</sub> , Nitrates	The treatment of greywater with Botryococcus algae species showed about 78% removal of COD, 90% removal of BOD <sub>5</sub> , 98% removal of nitrate	[129]
32 households in Sneek, Netherlands	Anaerobic biodegradability	COD, Nutrients, Surfactants	The maximum anaerobic biodegradability of greywater of 70 ± 5% shows the possibility of recovering the COD as methane. Aerobic treatment is observed to be more suitable than anaerobic treatment due to its low hydrolysis constant of the former system	[72]
Households in Egypt	Rotating biological contactor (RBC)	TSS, BOD <sub>5</sub> , TKN	On treating greywater with RBC, the observed average removal for TSS, BOD <sub>5</sub> , and TKN are 94.5%, 89.5% and 71% respectively	[126]
Hostel shower rooms	Sequential batch reactor (SBR)	Phosphate, Nitrate, Ammonia, and COD	About 90% of COD, 66% of phosphate, 50% of nitrate, and 91% of ammonia were removed by treating greywater through SBR	[123]
Residential areas Netherlands	Comparing aerobic treatment, anaerobic treatment (up-flow anaerobic blanket reactor), and combined anaerobic-aerobic treatment systems	COD, Nutrients, Surfactants	Aerobic treatment achieved removal of 90% COD and 97% anionic surfactants Anaerobic treatment achieved 51% COD removal, with a greywater methanisation rate of 32%, and poor removal (24%) of anionic surfactants. A combined anaerobic-aerobic system did not offer any further advantages Based on COD removal, sludge yield, and energy considerations, aerobic greywater treatment systems are preferred over anaerobic and combined anaerobic-aerobic systems	[125]
Single Household in Ethiopia	Modified Biofiltration and Phytoremediation (using constructed wetland)	Turbidity TSS, BOD <sub>5</sub> , COD, TN, TP, and FC	High pollutant removal efficiencies (97.2% turbidity, 99.2% TSS, 94% BOD <sub>5</sub> , 91.6% COD, 68.24% TN, 71.6% TP, and 89.9% FC) have been observed, recommending the system for greywater treatment in low-income tropical countries	[128]

to the usage of detergents, hot water for personal hygiene, and adherence of soil particles with the fabric. Trace levels of heavy metals concentration, mainly Zn, is observed in greywater due to the leaching of pipes. Elevated levels of Na and boron are noticed in greywater due to the usage of laundry cleaning chemicals. Limited research has been done on greywater's xenobiotics, color, and odor characteristics. Abundant water quantity in HICs tends to dilute the greywater, resulting in low contamination levels. Most treatment technologies adopted for treating greywater are highly energy-intensive techniques like SBR, MBR, UF etc. Non-energy intensive methods like sand or granular activated carbon filtration, phytoremediation systems are suitable for the treatment of greywater to a certain extent, while a combination of these systems does offer high pollutant removal efficiencies and better quality effluents in greywater treatment. Sustainable treatment technologies like phytoremediation are in the preliminary stage of their application into the greywater treatment system and needs further research focus. Greywater water quality and quantity tend to vary a lot from source to source, but as a whole, a high amount of greywater is produced from HICs with a low level of contamination compared to LICs. So appropriate technologies must be developed in the view of sustainability for LICs. Since LICs are profound to low water availability, recycling greywater appears to be an attractive option over a paradigm existence.

Altogether, with greywater having a high reuse potential at the point of generation, appropriate greywater treatment can play a pivotal role in achieving Sustainable Development Goal (SDG)-6: Clean water and sanitation.

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**Data availability** All data and materials are included in the manuscript.

## Declarations

**Competing interests** The authors declare that they have no competing interests.

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